



Cryogenic Fluid Management

Technology Development Roadmaps

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In-Space Chemical Propulsion
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CFM Technology Development Roadmaps

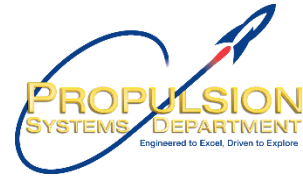


OBJECTIVE(S):

- Outline a CFM Technology development path to support the long duration missions envisioned by the agency.
- Identify which CFM elements are likely to be needed:
 - Based on the 2020 Decision Point to determine the In-Space Stage Architecture
 - Lander & Ascent Vehicle Architectures
- Identify technology development “long poles”
- Identify which technologies require a flight demonstration to achieve TRL 6
- Path to TRL 6 to support the In-Space Stage PDR which is tentatively scheduled for 2023
- Identify which development efforts are currently funded and the state of technology maturation once the effort is complete.
- Effort includes the CFM communities at GRC and MSFC including personnel from STMD
- Provide final product in the form of a White Paper to AES, STMD, etc



CFM Technology Development Roadmaps



BACKGROUND:

- **Advancement in Cryogenic Fluid Management (CFM) Technologies is essential for achieving NASA's future long duration missions.**
- **Current State Of the Art (SOA) CFM technologies enable cryogenic propellants to be stored for several hours. However, some envisioned mission architectures require that cryogenics to be stored for two years or longer.**
- **All functions are required to perform both with and without the presence of a gravitational field or acceleration.**
- **Which CFM technologies are required is a function of the cryogenics used, mission architecture, vehicle design and propellant tank size.**



What are the Fundamental CFM Responsibilities?

- **Store propellant:** Reduce heat leak and gauge propellant level

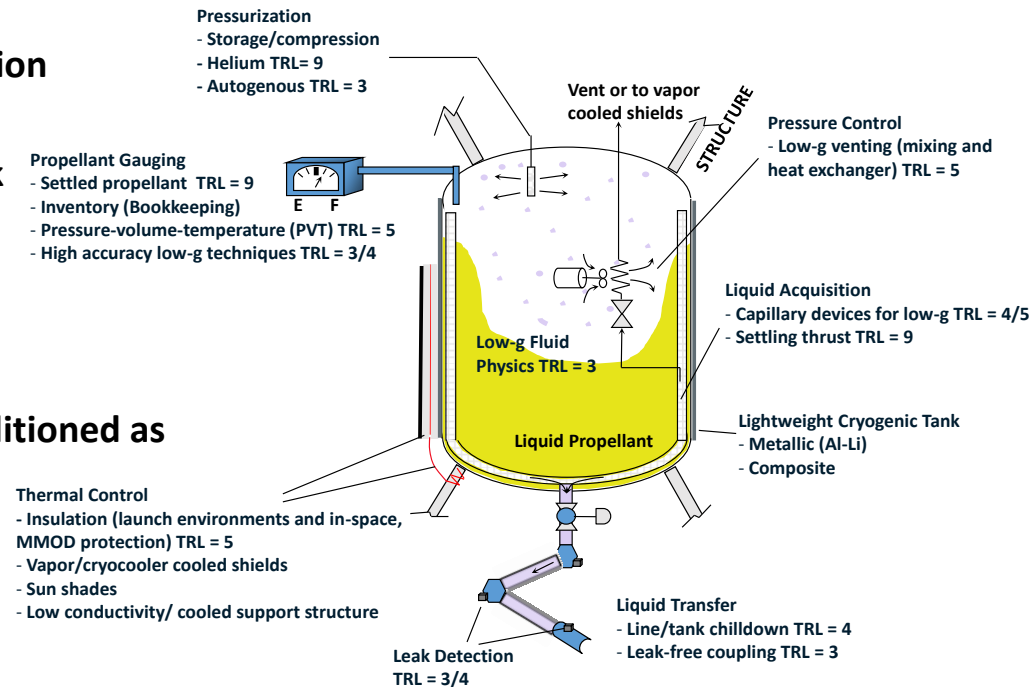
- Tank and structure insulation
- Passive and active cooling
- Liquid level and mass gauging instrumentation

- **Control pressure:** Ameliorate effect of heat leak

- Venting
- Mixing
- TVS / Active Cooling (Cryocoolers)

- **Deliver propellant:** Provide liquid or vapor conditioned as required

- Start and run box conditioning
- Settled transfer
- LADs & PMDs
- No-vent fill





Definitions / References



“Cross Cutting”- Term used to define a technology that is applicable for all cryogenics.

Examples include most insulation concepts, settled / unsettled liquid level mass gauging and helium pressurization systems.

“Fluid Specific”- Defines a technology that is only applicable for a specific fluid. Examples include autogenous pressurization, LADs, PMDs, and Cryocoolers.

“Hard Cryogenics” – LH2

“Long Duration” – A mission requiring cryogenics to be stored for extended periods of time requiring Active Cooling via Cryocoolers. Examples include In-Space NTP, and Mars and Lunar Ascent/Descent Vehicles.

“Settled” – The location of the liquid interior to the propellant tank is driven by the presence of a gravitational field.

“Short Duration” – A mission requiring cryogenics to be for a short enough period of time that Active Cooling via Cryocoolers is not required (typically a few hours to ~ 30 days). Examples include SLS EUS and Centaur.

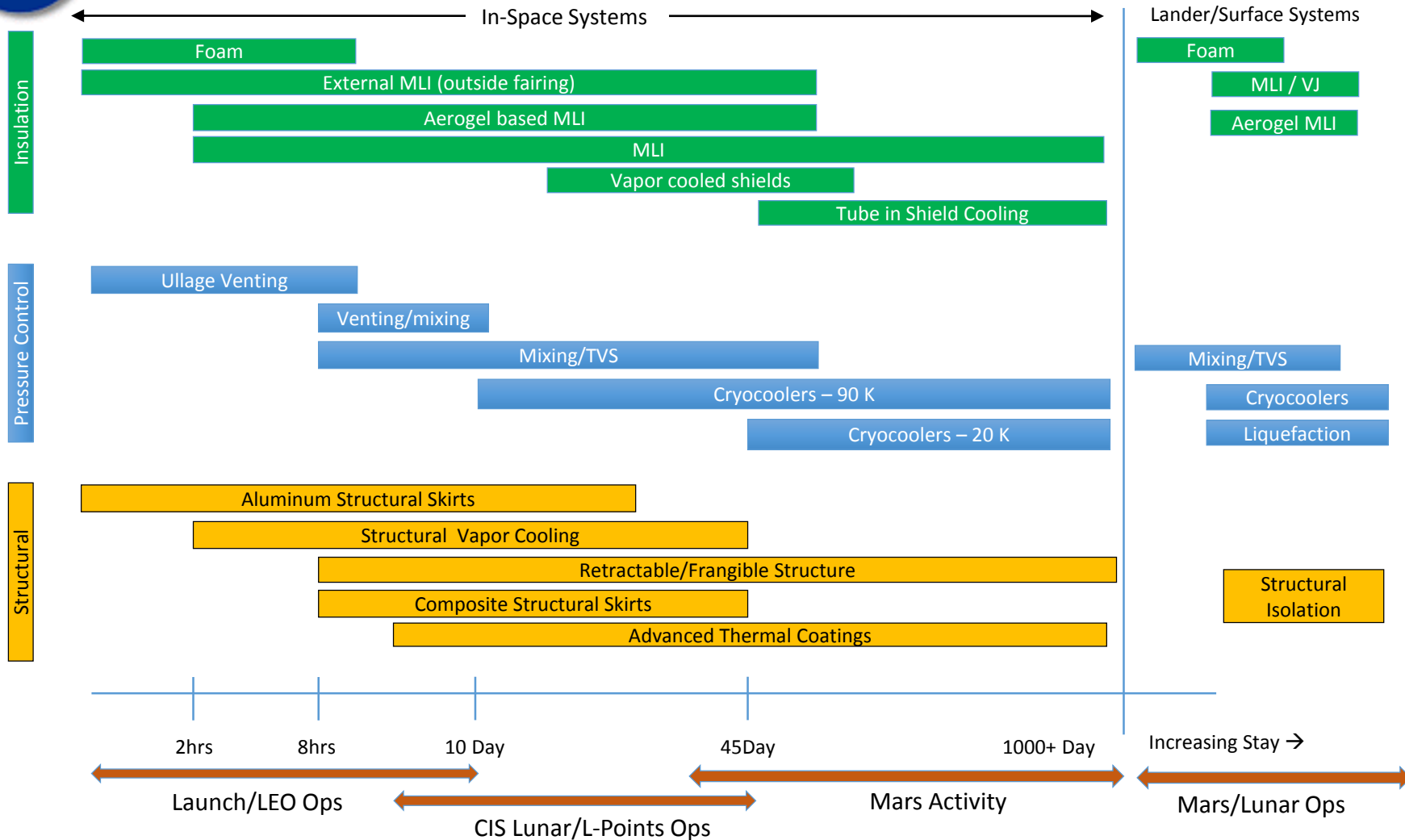
“Soft Cryogenics”- Essentially any cryogenics other than LH2. Examples include LOX, LCH4 and LNG.

“Unsettled” – Liquid propellant is attached to the tank inner walls with the ullage taking a spherical shape at the tanks center. In micro-g, surface tension effects dominate gravitational forces.



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Technology Application for Thermal Management of Cryogenic Fluids



Other CFM Technologies:

- Mass Gauging - Independent of mission time – as needed operationally (settled or unsettled)
- Pressurization - Independent of mission time – as needed for fluid transfer or engine operation can be provided by IVF
- Liquid Acquisition - Independent of mission time – as needed for RCS or fluid transfer (settling can minimize the need for this technology)
- Fluid Transfer - Independent of mission time – as needed depending on operations/depot usage/ISRU/Refueling/Landers



CFM Technologies Requiring Maturation

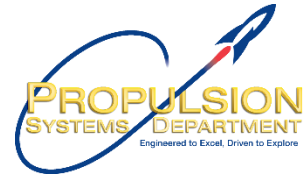


There are a total of eighteen CFM technologies identified to support an In-Space Stage and a Lander/Ascent Vehicle, six of which require further development before a flight demonstration and are considered *“gaps needing development”*.

CFM Elements					
Technologies	Current TRL	Gravity Dependant (Y/N)	Path to TRL 6	"Cross Cutting" or "Fluid Specific"	
Multilayer Insulation	5	No	Ground Test	Cross Cutting	Can achieve TRL 6 through ground testing.
Low Conductivity Structure	5	No	Ground Test	Cross Cutting	
Tube-On-Shield BAC	5	No	Ground Test	Cross Cutting	
Tube-On-Tank HTX	5	Yes	Flight Demo	Cross Cutting	Flight Demo required to achieve TRL 6.
Thermodynamic Vent System	5	Yes	Flight Demo	Cross Cutting	
MPS Line Chill	5	Yes	Flight Demo	Cross Cutting	
Helium Pressurization	5	Yes	Flight Demo	Cross Cutting	
Unsettled Liquid Mass Gauging	5	Yes	Flight Demo	Cross Cutting	
Pump Based Mixing	5	Yes	Flight Demo	Cross Cutting	
Autogenous Pressurization	5	Yes	Flight Demo	Fluid Specific	
Liquid Acquisition Devices	5	Yes	Flight Demo	Fluid Specific	Technology “Long Poles” Development is needed. Can achieve TRL 6 through ground testing.
Advanced External Insulation	3	No	Ground Test	Can Be Both	
High Capacity, High Efficiency Cryocoolers 90K	3	No	Ground Test	Cross Cutting	
Soft Vacuum Insulation	3	No	Ground Test	Cross Cutting	
Valves, Actuators & Components	3	No	Ground Test	Cross Cutting	
High Capacity, High Efficiency Cryocoolers 20K	3	No	Ground Test	Fluid Specific	
Liquefaction Efficiencies (MAV & ISRU)	4	No	Ground Test	Fluid Specific	
Vapor Cooling	4	No	Ground Test	Fluid Specific	



EMC system CFM Technology Priorities



Based on initial review of the EMC architecture (landers and stages), the following technologies are prioritized:

- **Stages (Split Architecture, Methane Cryogenic Propulsion Stage):**
 - High capacity cryocoolers (~100 W @ 90 K) integrated into a single tank cooling distribution system
 - Pressure Control (TVS, mixing)
 - Mass Gauging (settled is baselined)
 - Valves to meet flow, heat load, and leakage requirements
 - Helium Conditioning/Storage and Pressurization
- **Landers (Ascent and Descent Stages, All Architectures)**
 - High capacity cryocoolers (~100 W @ 90 K) integrated across multiple tank cooling and oxygen liquefaction systems
 - Insulation systems for the surface of Mars (5 Torr)
 - Pressure Control (TVS, mixing)
 - Mass Gauging (settled and unsettled)
 - Low-g propellant acquisition



NTP & Aggregation / Depot System CFM Technology Priorities

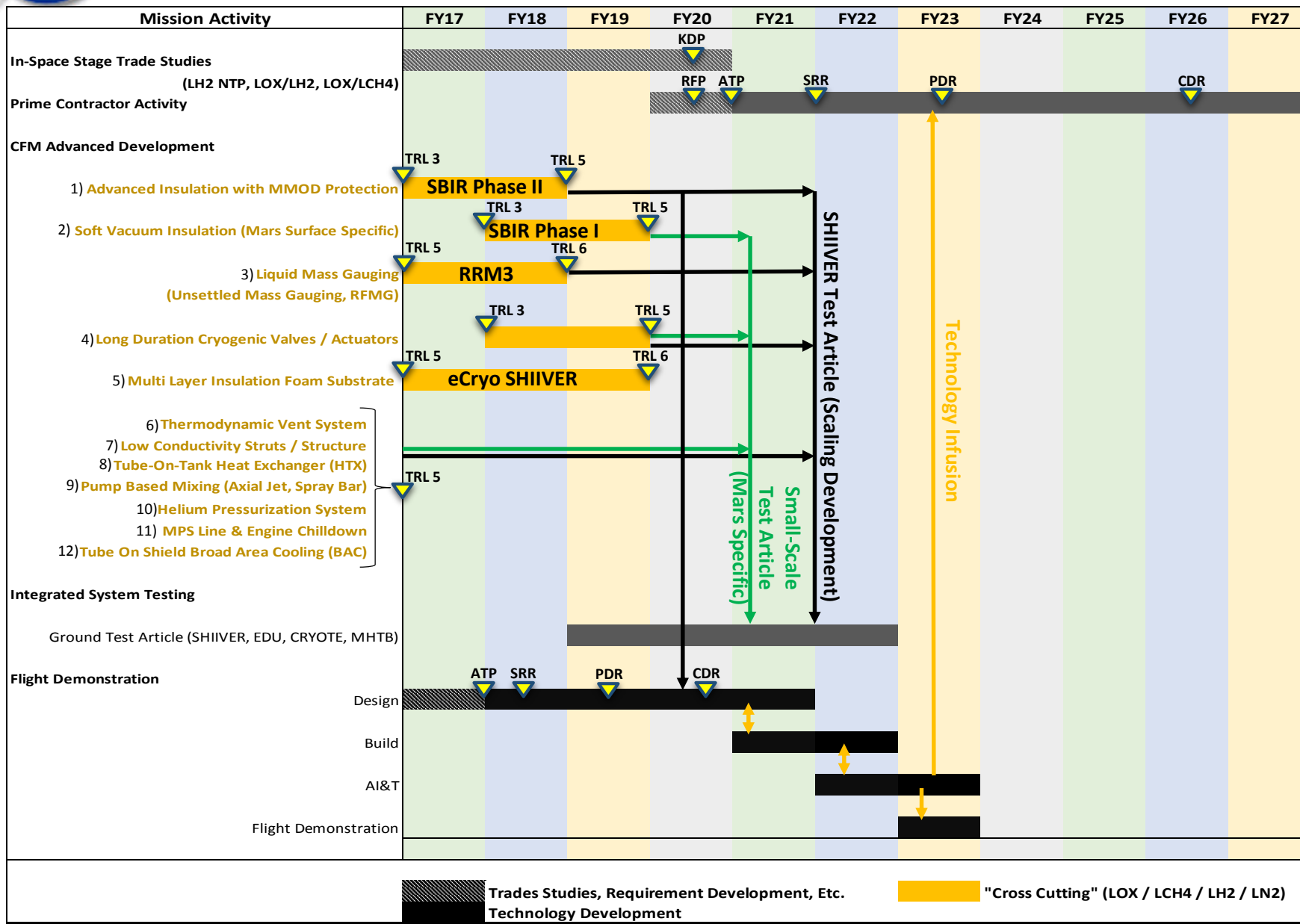


- **Nuclear Thermal Propulsion**
 - 20 K Cryocoolers (up to 225 W lift needed) – need to compare 20 K only and 20 K + 90 K rejection scenarios
 - Autogenous pressurization
 - External MLI outside fairing (assuming in-line tanks)
 - Quick Disconnects/Automated Couplings for engine feedlines
 - Transfer between tanks (multiple drop tanks and refueling tanks), currently assuming settled

- **Lunar Aggregation/Depot Scenarios**
 - Assumed ZBO storage, didn't size storage system (production starts 2030)
 - Fluid transfer (large quantities) in lunar and Martian orbits (autogenous)
 - Autogenous couplings
 - Lots of reuse and common sizing

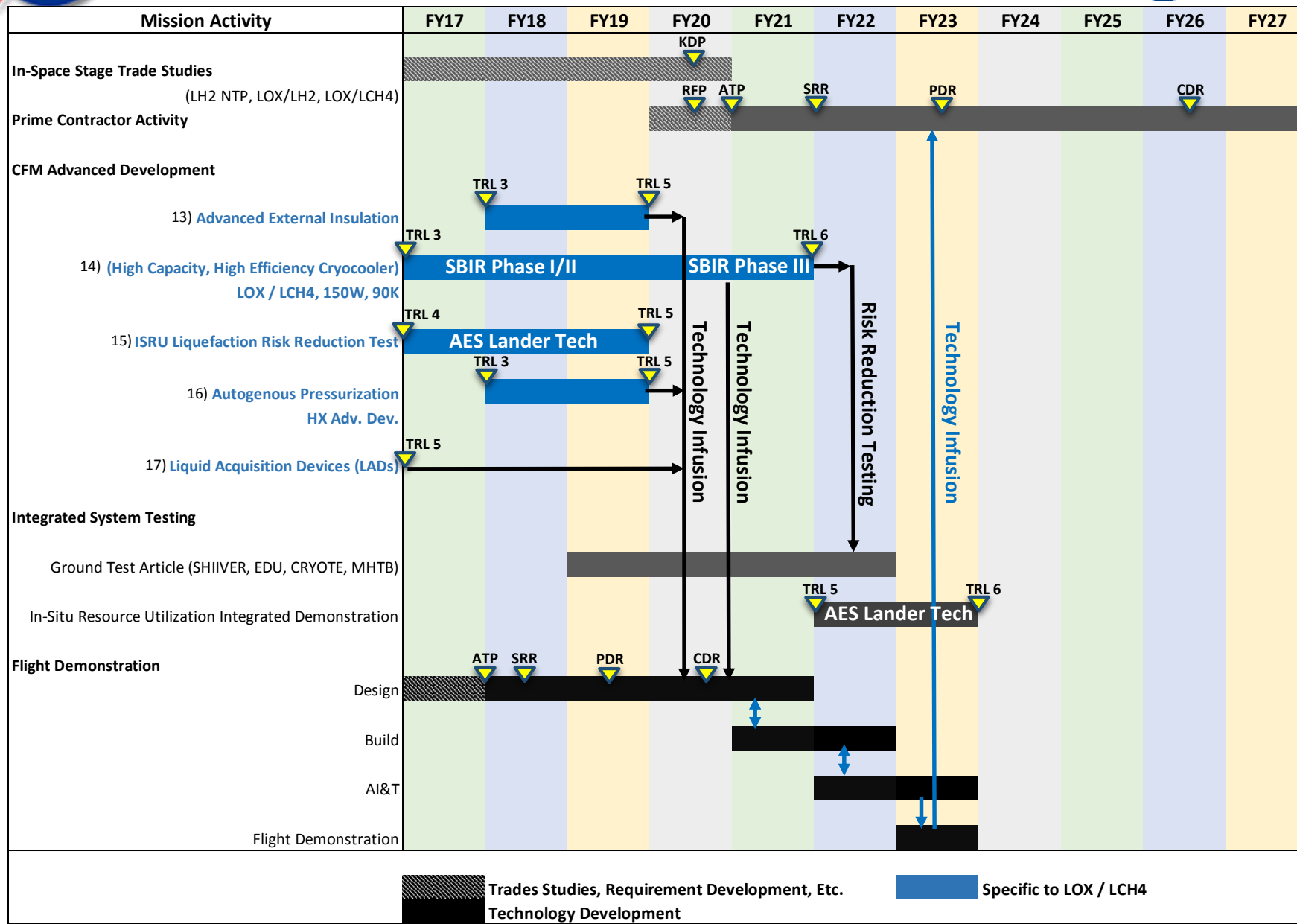


CFM Development Roadmap – “Cross Cutting”



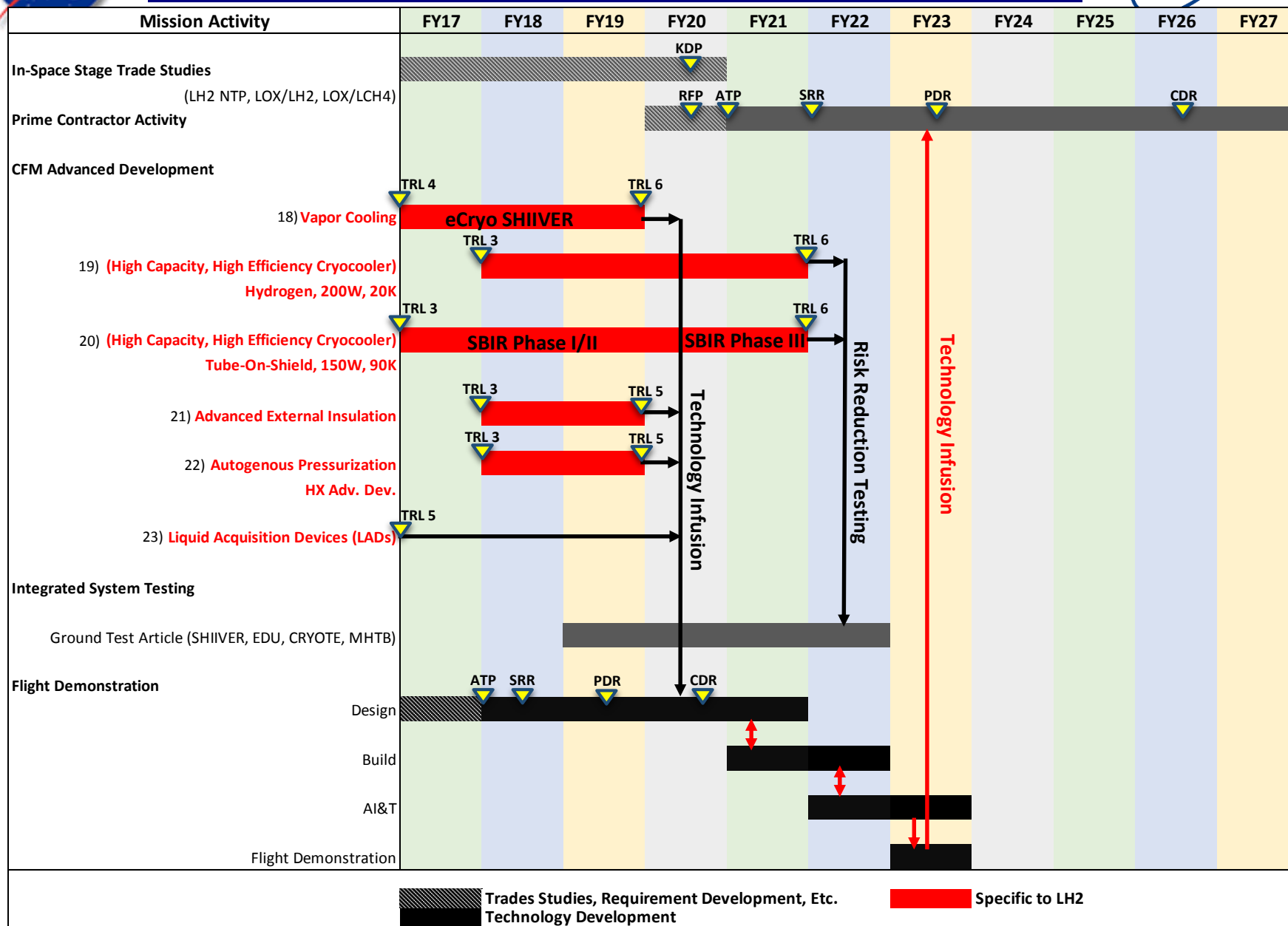


CFM Development Roadmap – Fluid Specific - LOX/LCH4





CFM Development Roadmap – Fluid Specific – LH2





Demonstrations Summary and Differences



	In-Space Stage (LH2/LO2)	In-space Stage (LCH4/LO2)	Nuclear (LH2)	Ascent Stage (LCH4/LO2)	ISRU based System (production)(L O2)	Descent Stage (LCH4/LO2)	Lunar Aggregation (no production)
Demonstration Tank Diameter (m)	3	2	3	1	TBD	1	2
Test Fluid	Hydrogen	Methane	Hydrogen	Methane	Oxygen	Methane	Hydrogen?
Duration	Several months (2-6)	Several months (2-6)	6 – 12 mo	Up to a year (reliability)	Months to a year	Up to a year (reliability)	6 mo
Location	LEO	LEO	Cis-Lunar	Cis-Lunar	Ground	Cis-Lunar	LEO/Cis-Lunar
Cryocooler	No	Yes – 90 K	Yes – 20 K Maybe – 90 K	Yes – 90 K	Yes – 90 K	Yes – 90 K	Maybe
Storage	Yes; TVS pressure control + low heat load tank	Yes; Cryocooler vs. TVS	Yes; Cryocooler + Min Heat Load Tank (External MLI?)	Yes; Cryocooler + Min Heat Load Tank	Yes; Cryocooler + Min Heat Load Tank	Yes; Cryocooler + Min Heat Load Tank	Yes; Cryocooler vs. TVS + Min Heat Load Tank
Transfer	No; (currently no reqmts)	No; (currently no reqmts)	Yes	End of Life RCS?	In gravity field	RCS?; Initial Expulsion?	Yes – partially full vs. empty?
Unsettled Gauging	No; (currently no reqmts)	No; planned settling maneuvers	Yes	Yes	No	Yes	Yes
Special Conditions/ questions	In-line LH2 barrel?; minimize heat load into tank	Helium vs. autogenous pressurization	Heaters to simulate engine heat dumps?; Automated couplings	Risk of added TVS with cryocooler; MMOD?; soft vacuum insulation	Soft vacuum insulation	Risk of added TVS with cryocooler; MMOD?; soft vacuum insulation	Automated couplings; autogenous pressurization;



Conclusions



- All CFM technologies must be matured to TRL 6 to be infused in the In-Space Stage Design for PDR which is scheduled for 2023.
- Gravity independent technologies can be matured to TRL 6 via ground testing, but gravity dependent technologies must successfully be demonstrated in flight.
- Some elements still require technology development (TRL 4 or less) and unless funding is infused to accelerate the development process, there is significant risk that the technologies will not be available in time.
- Need to understand the In-Space Architecture to design the appropriate flight demonstration
 - Some technologies are “cross cutting” and others are “fluid specific”.
 - Appropriate scaling needs to be taken in account when sizing the flight demonstration.
 - The flight demonstration preliminary design must be flexible enough at PDR to accommodate the requirements once a 2020 decision is made.
 - To meet schedule, the flight demonstration PDR will likely have to be before the 2020 KDP.
- If LOX/LH2 or NTP is selected for the In-Space Architecture, then a second flight demonstration may be needed to support LOX/LCH4 MAV/Lander.
- Based on CPST, a flight demonstration will take six years and ~\$200M.
- Need to get started NOW!!!



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Backup Charts



List of Acronyms



AES	Advanced Exploration Systems	LOX	Liquid Oxygen
AFRC	Armstrong Flight Research Center	LSP	Launch Services Program
ATP	Authority to Proceed	MAV	Mars Ascent Vehicle
BAC	Broad Area Cooling	MCU	Motor Compressor Unit
CCSC	Collaborations of Commercial Space Capabilities	MHTB	Multi Purpose Hydrogen Test Bed
CDR	Critical Design Review	MLI	Multi Layer Insulation
CFM	Cryogenic Fluid Management	MMOD	Micro Meteoroid Orbital Debris
CO2	Carbon Dioxide	MPS	Main Propulsion System
COPV	Composite Overwrap Pressure Vessel	MSFC	Marshall Space Flight Center
CPST	Cryogenic Propellant Storage and Transfer	NTP	Nuclear Thermal Propulsion
CryoFOSS	Cryogenic Fiber Optic Sensing System	PDR	Preliminary Design Review
CRYOTE	CRYogenic Orbital Testbed	PMD	Propellant Management Devices
DVAT	Development & Validation of Analysis Tools	RCS	Reaction Control System
eCryo	Evolvable Cryogenics	RFMG	Radio Frequency Mass Gauging
EDU	Engineering Development Unit	RFP	Request for Proposal
ESTF	Exploration Systems Test Facility	RRM3	Robotic Refueling Mission 3
EUS	Exploration Upper Stage	SBIR	Small Business Innovation Research
FOSS	Fiber Optic Sensing System	SHIIVER	Structural Heat Intercept Insulation Vibration Evaluation Rig
FY	Fiscal Year	SLS	Space Launch System
GFRC	Goddard Flight Research Center	SOA	State Of the Art
GRC	Glenn Research Center	SOFI	Spray On Foam Insulation
HTX	Heat Exchanger	SRR	System Requirements Review
IFUSI	Improved Fundamental Understanding of Super Insulation	STMD	Space Technology Mission Directorate
ISRU	In-Situ Resource Utilization	TE	Tech Excellence
IVF	Integrated Vehicle Fluids	TIP	Technology Investment Program
JSC	Johnson Space Center	TRL	Technology Readiness Level
JT	Joule Thomson	TVS	Thermodynamic Vent System
K	Kelvin	ULA	United Launch Alliance
KDP	Key Decision Point	VATA	Vibro Acoustic Test Article
KSC	Kennedy Space Center	VCMLI	Vacuum Cell Multi Layer Insulation
LADs	Liquid Acquisition Devices	VJ	Vacuum Jacket
LH2	Liquid Hydrogen	W	Watts
LN2	Liquid Nitrogen	ZBO	Zero Boil-Off
LNG	Liquid Natural Gas		



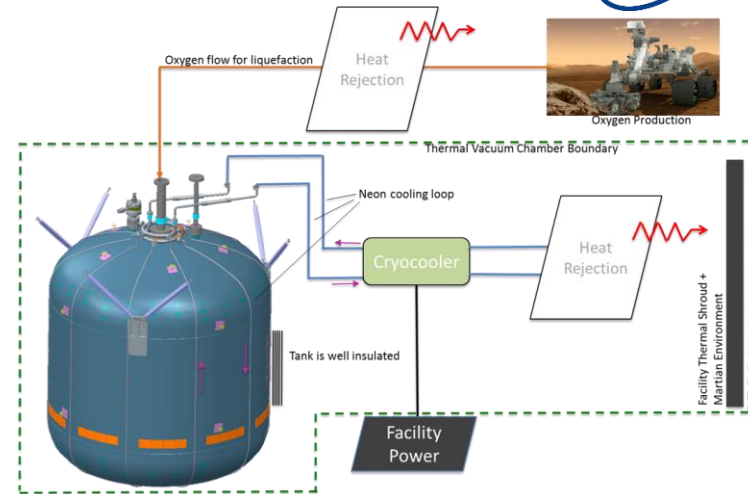
Current Technology Development Efforts

AES – Lander Tech

- **ISRU Liquefaction Risk Reduction Testing**
 - Demonstrate liquefaction of “ISRU Like” propellants using active cooling and tube-on-tank HTX configuration.
 - Testing conducted at MSFC (LN2), then GRC (LOX) – FY17 thru FY19
 - Fully integrated system demo at JSC – FY22 to FY23

KSC LSP CCSC

- **CRYogenic Orbital TESTbed (CRYOTE 3)**
 - “Flight Like” Propellant tank
 - Measurements of Heat Load, Apparent Density, and Thermal Stratification
 - Includes AFRC’s Fiber Optic Sensing System (FOSS) for measurements of both temperature and strain
 - Includes AFRC’s mass gauging technology CryoFOSS
 - Phase I – Funded by KSC LSP & CCSC
 - Completed in Spring FY15
 - Insulated to match targeted heat loads
 - LN2 and LH2
 - Phase II – Funded by KSC LSP, CCSC, and MSFC Scheduled for Spring of FY17
 - LN2 and LNG



Liquefaction Test Diagram



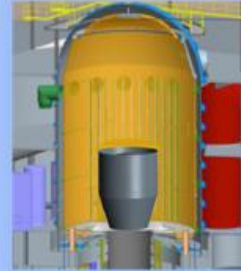
CRYOTE 3 Test Article



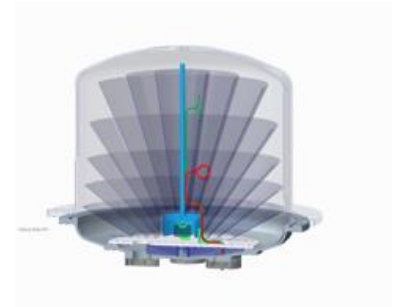
Current Technology Development Efforts

Evolvable Cryogenics (eCryo)

- **Structural Heat Intercept Insulation Vibration Evaluation Rig (SHIIVER)**
 - Representative of a large-scale cryogenic tank
 - Implement vapor cooling and multi-layer insulation (MLI)
- **Radio Frequency Mass Gauging (RFMG)**
 - Unsettled propellant mass gauging
 - Developed at GRC, tested at MSFC
 - Scheduled to fly on RRM3
- **Improved Fundamental Understanding of Super Insulation (IFUSI)**
 - Improving the design capabilities of MLI blankets to large-scale, cryogenic tanks
- **Development & Validation of Analysis Tools (DVAT)**
 - Advancement of numerical tools to cover cryogenics in both settled and unsettled conditions.
- **Integrated Vehicle Fluids (IVF)**
 - Evaluate the extensibility of the IVF concept for use on Exploration Upper Stage (EUS)



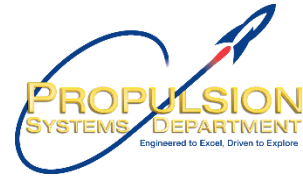
SHIIVER Test
Article



RFMG for RRM3
Mission



Current Technology Development Efforts



SBIR Funded Activities

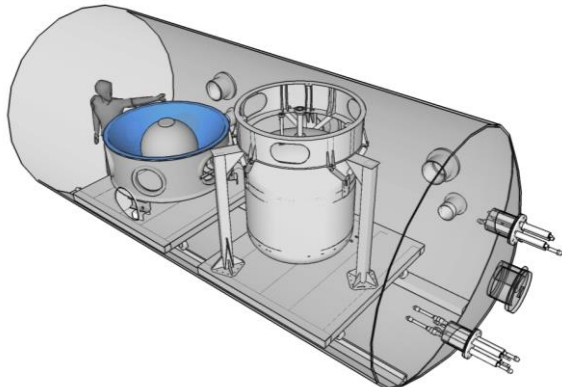
- Advanced Insulation Development – Two Phase II
- High Efficiency, High Capacity “Flight Like” 150W/90K Cryocooler – Two Phase I

SBIR/GCD Funded

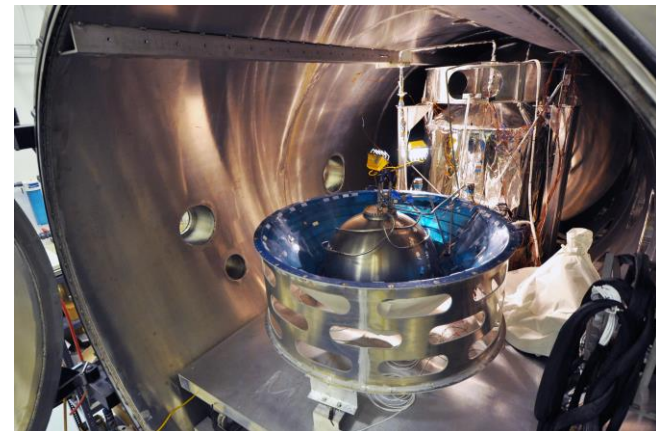
- “Flight Like” 20W/20K Cryocooler – Phase III

Other Funding Sources

- Vented Chill / No-Vent Fill
 - VATA to CRYOTE 1 Propellant Transfer
 - Minimize propellant loss during an on-orbit transfer (Propellant Depot)
 - Chill Transfer line only once
 - Does not require mass gauging or flow measurement



Exploration Systems Test Facility (ESTF)



VATA and CRYOTE 1 in ESTF